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TECHNICAL MEMORANDUM [illegible]

SHAPED CHARGE SCALING

OSCAR A. KLAMER

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PICATINNY ARSENAL
DOVER, NEW JERSEY

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TECHNICAL MEMORANDUM 1383

SHAPED CHARGE SCALING

BY

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MARCH 1964

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TABLE OF CONTENTS

FOREWORD

~~This~~ memorandum was prepared to provide a brief unclassified presentation of basic concepts, elementary design criteria and scaling techniques for shaped charges. The information is intended for individuals with little or no background in this field of munitions to provide them with sufficient data to understand design requirements for simple shaped charge items.

Recent literature in this field covers more advanced methods used to maintain or enhance shaped charge performance; however that information is classified and therefore not suitable for inclusion in this report.

Source materials for this memorandum have been obtained from textbooks, articles and various government publications and reports. These are listed on the "References" page.

SHAPED CHARGE SCALING

The design of shaped charge items is governed by two primary considerations -- the required target penetration and the allowable configuration permitted by the delivery technique to be used. The penetration characteristics have been studied extensively to establish the effects of explosive, explosive configuration, size, liner material and shape, orientation relative to the target, spin and symmetry.

The depth of primary penetration, P^1, depends upon the jet length, L, and the ratio of the jet density, ρ_j to the target density, ρ . Actually it is described more exactly as:

$$P' \approx L \sqrt{\frac{\rho_j}{\rho}}$$

As can be seen from this relationship, the strength of the target material does not have any appreciable effect on the depth of primary penetration. Since the ultra-high velocity of the impinging jet develops pressures far in excess of target yield strengths, the jet and target act like incompressible fluids, and the target strength can be neglected.

The secondary penetration effect, produced by the lower velocity tail of the jet, does vary with target yield strength. Since the tail velocity will only impart pressures in the range of the yield strength of mild steel, the penetration into homogeneous armor is 10 to 15% less than mild steel.

Basically scaling of a shaped charge depends on the use of the appropriate materials, geometry, and spacing which will result in optimum values for jet length and density to match the target requirements.

Although maximum penetrations in mild steel of up to 12 cone diameters may be feasible, actual penetrations are limited to ½ to 2/3 of that depth because optimum conditions are rarely possible under field conditions.

The critical factors, which control the jet properties and formation, will be discussed in terms of their affect on target penetration.

EXPLOSIVE PROPERTIES

The penetration of the jet has been shown to correlate with the explosive detonation pressure. Since the detonation pressure is related to the square of the detonation rate, it can be said that the greatest effect will be produced by the explosive having the highest rate of detonation.

The following table relates the efficiency of four castable explosives:

TABLE 1 (From Reference 8)

Explosive	Density gm/cc	Detonation Rate meters/sec	Relative Penetration Efficiency
Composition B	1.68	8,000	1st
Pentolite	1.64	7,640	2nd
Ednatol	1.62	7,500	3rd
TNT	1.59	6,900	4th

CAVITY LINERS

A variety of liner geometries have been studied to determine the most desirable liner configuration. The investigations have included cones, hemispheres, cylinders, trumpet shapes, and various combinations of these. The effects achieved vary due to the way in which different shaped cavities react. For example, a conical liner collapses from the apex and leaves 70 to 80% of the liner to follow the jet as a slug. On the other hand, hemispherical liners appear to turn inside out, and most of the liner is projected in the jet; however, rather large standoffs (3 to 4 cone diameters) are necessary for effective use.

Because of penetration characteristics, cones have become almost standard with other shapes used occasionally for special applications. Therefore, the remaining discussion will relate primarily to cone shaped liners and the effects of varying cone parameters.

In general the effectiveness of the cone shaped charge will be discussed in terms of the following dimensions:

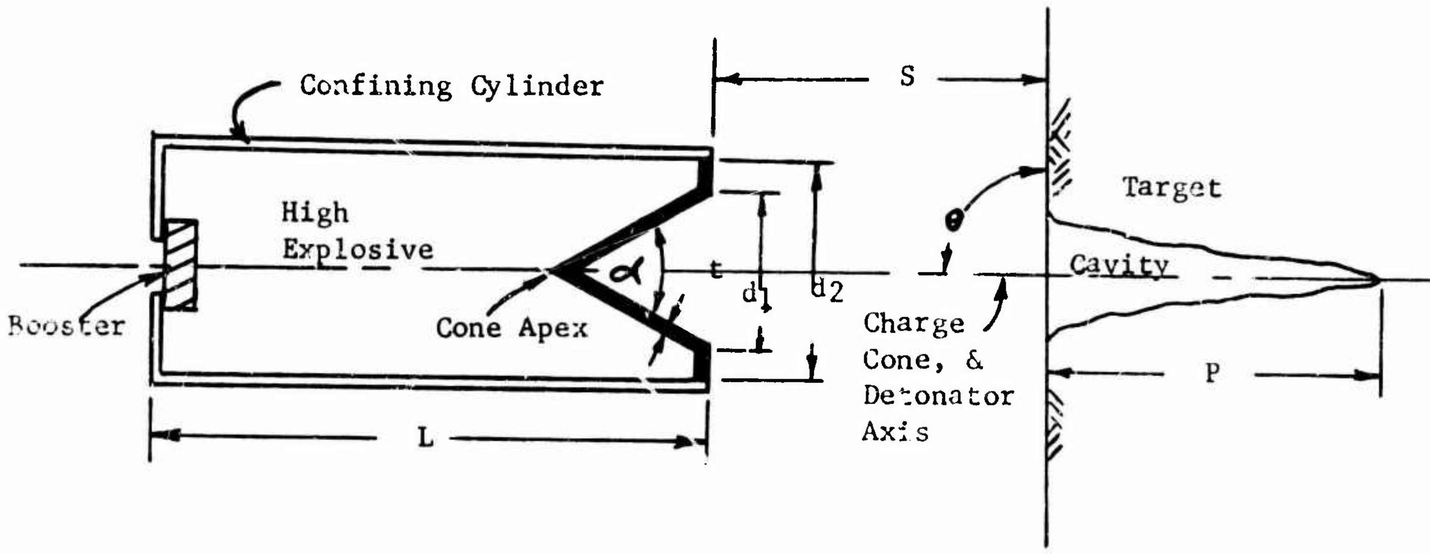


Figure 1

P - target penetration
S - standoff distance
L - charge length
t - liner thickness

α - cone apex angle
θ - target orientation angle
d_1 - cone diameter
d_2 - charge diameter

Liner Material

The material from which the liner is fabricated has a very marked effect on target penetration. The physical properties of the liner material, which are considered important, are the density, ductility and melting or boiling point. The liner density directly affects the jet density, ρ_j, which should be high for the greatest penetrations.

It is thought that greater ductility, under high stress, will provide improved performance because more material can be pulled from the base of the liner after collapse. This would result in reinforcing the tail end of the jet, thereby increasing the over-all penetrating power. The British have felt that relatively low boiling metals such as lead, tin, and cadmium would definitely melt and to a certain extent even vaporize during jet formation forming a more continuous jet.

The following Table 2 will demonstrate the effect of liner material on target penetration, using constant standoff, for cones of 90° apex angle and 1 mm liner thickness:

TABLE 2 (From Reference 8)

Metal Group	Approx. Sp. Gr. of Liner Metal	Hole Depth mm	Hole Width mm
Copper and Copper Alloys	8.5	58	14
Deep drawing sheet steel	7.7	55	15
Zinc	7.2	51	17
Sheet iron	7.8	47	16
Aluminum	2.7	29	23
Magnesium alloys	1.7	23	25

Several points should be noted from this data:

The depth of penetration is related to the specific gravity of the liner metal.

There is no appreciable difference in penetration using cones of metal within the same group -- copper and copper alloys.

As the depth of the hole decreased, the width of the cavity increased, so that the hole volume in all cases was practically unchanged.

These results were obtained for a particular set of conditions. The relative effectiveness of different metal cones might be altered, if the conditions are changed.

Jet penetrations will be increased if the jet can lengthen appreciably before breaking up. This lengthening ability is governed to a great extent by the metallurgical properties of the jet. Aluminum and copper both have such superior characteristics. Therefore, a high density liner exhibiting these properties will be most effective for target penetrations. More specific effects of liner material on charge design will be covered under other discussions of parameters.

Liner Thickness

The optimum liner thickness will vary with the cone angle, charge confinement, and liner material as indicated in the following Figure 2 and 3:

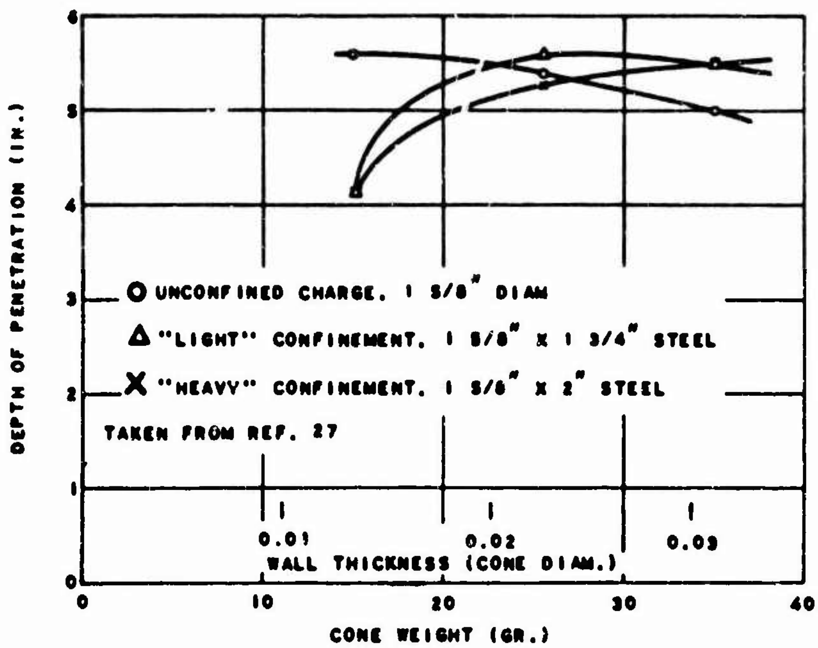


Figure 2. Depth of Penetration vs. Wall Thickness
(Reproduced from Figure 5, Reference 3)

Figure 2 points up the possible need for slightly thicker liners as charge confinement is increased.

It has been concluded from various studies that optimum liner thickness for a given metal is proportional to the sine of one-half the cone apex angle; however, the relationship may be somewhat greater for cones more acute than 45°.

In Figure 3 the range of values indicated for each liner metal reflects those in common usage.

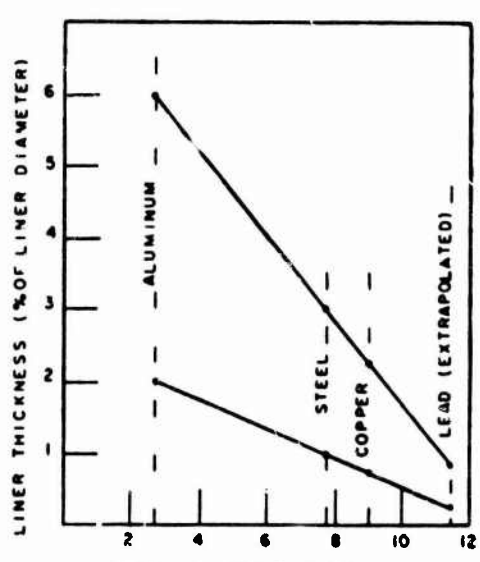


Figure 3. Liner thickness versus density of liner Material showing the Range of values in Common usage. (From Figure 1 of Reference 18)

From this liner data, we can conclude that, in general, liner thickness for cones of various materials should be between 0.01 and 0.06 cone diameters. The optimum wall thickness for steel cones with various charge confinements (Figure 2) is also about right for 45° copper cones.

If one chooses the appropriate cone weight, confinement has no net effect upon the penetration. Other conditions being constant, increased liner thickness results in smaller diameter holes.

Non-uniform cone walls can be used to alter jet characteristics somewhat. Figure 4 summarizes some liner designs and the resultant cavity effects.

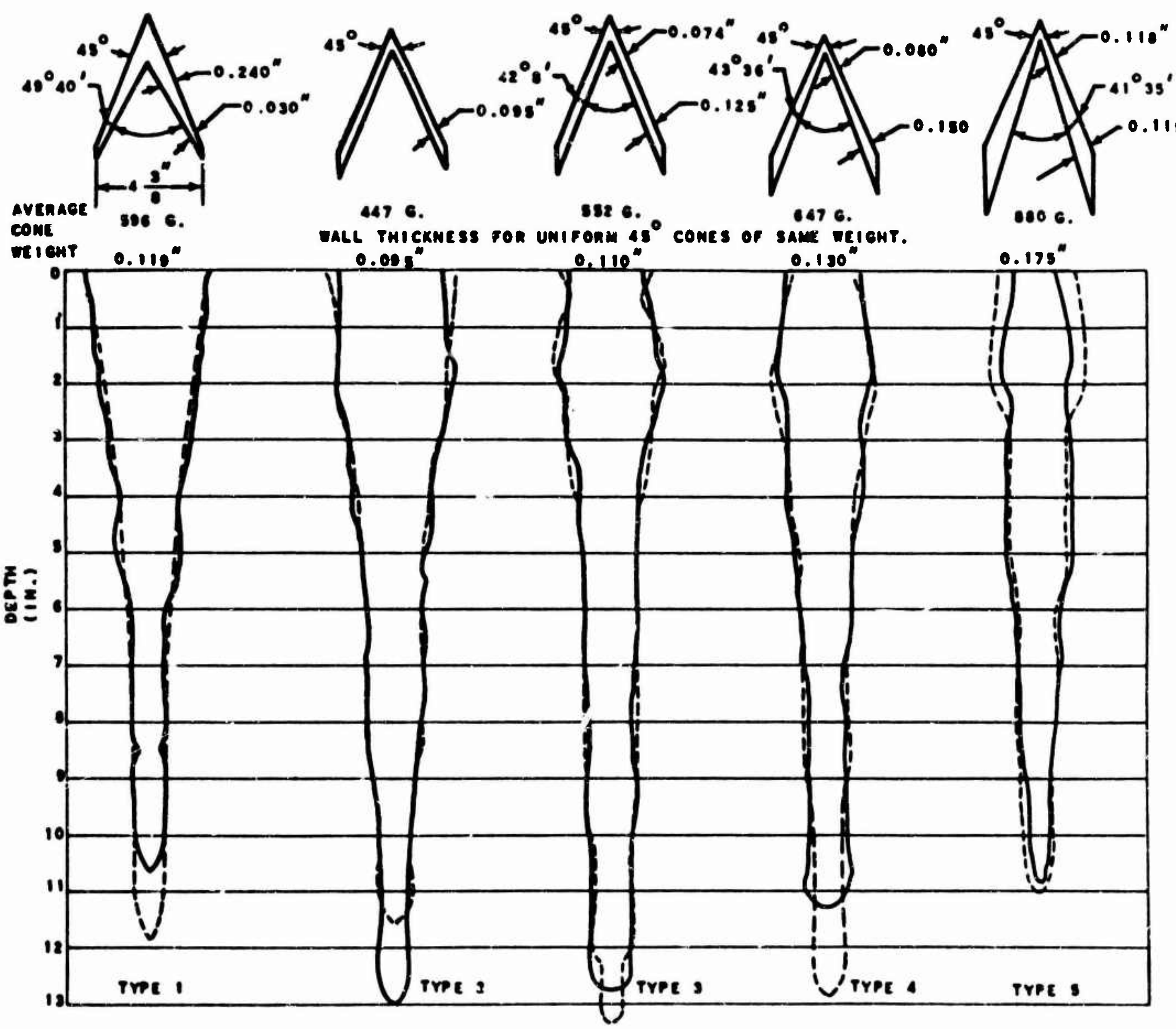


Figure 4. Steel Target Penetration by 4-3/8" Diameter Steel Cones have Tapered Walls. Confinement 1/16"; stand-off, 6". (Reproduced from Figure 4, Reference 3.)

CHARGE SHAPE AND SIZE

The depth of penetration is a function of both the charge diameter and charge length; however, increasing charge length beyond three to five cone diameters does not significantly increase performance as indicated in Figure 5.

For 1-5/8" Steel Cones (44°) at 3" standoff.

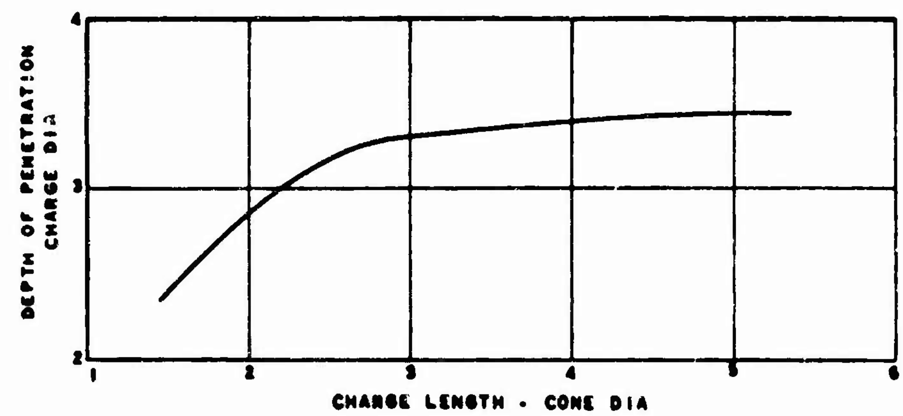


Figure 5. Depth of Penetration vs. Charge Length (Reproduced from Figure 2, Reference 3)

The translated German documents indicate the following relationship for varying cone diameter at constant charge diameter.

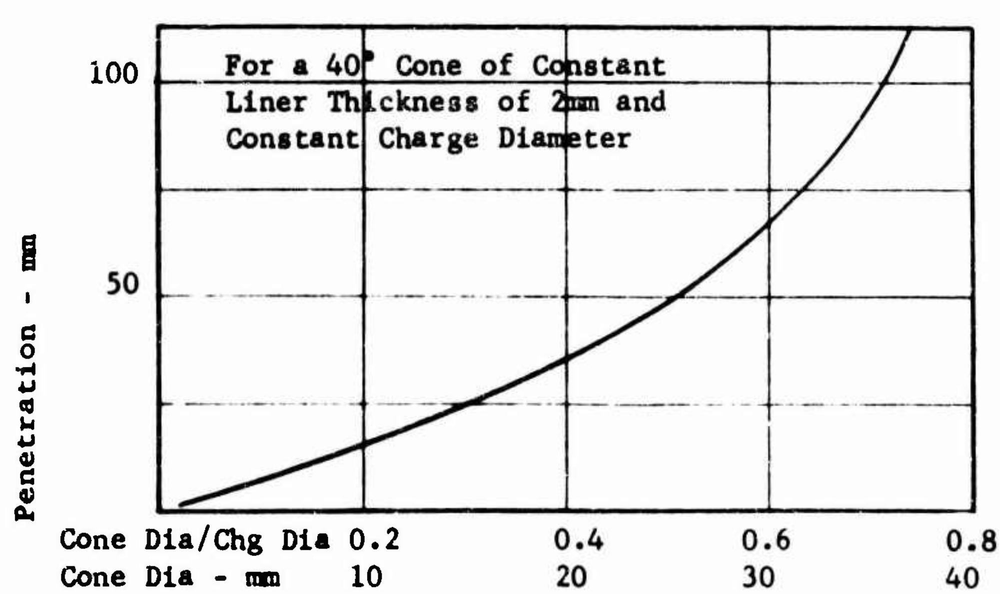


Figure 6. Depth of Penetration vs. Cone to Charge Diameter Ratio. (Taken from Figure 7 of Reference 16)

Utilization of the maximum cone diameter is apparent from Figure 6; however, for a fixed charged diameter beyond a certain cone size improvement does not continue because a minimum width of explosive layer is necessary, for the charge to function properly.

Another relationship found in the German documents is the effect on penetration when varying charge diameter with constant cone diameter.

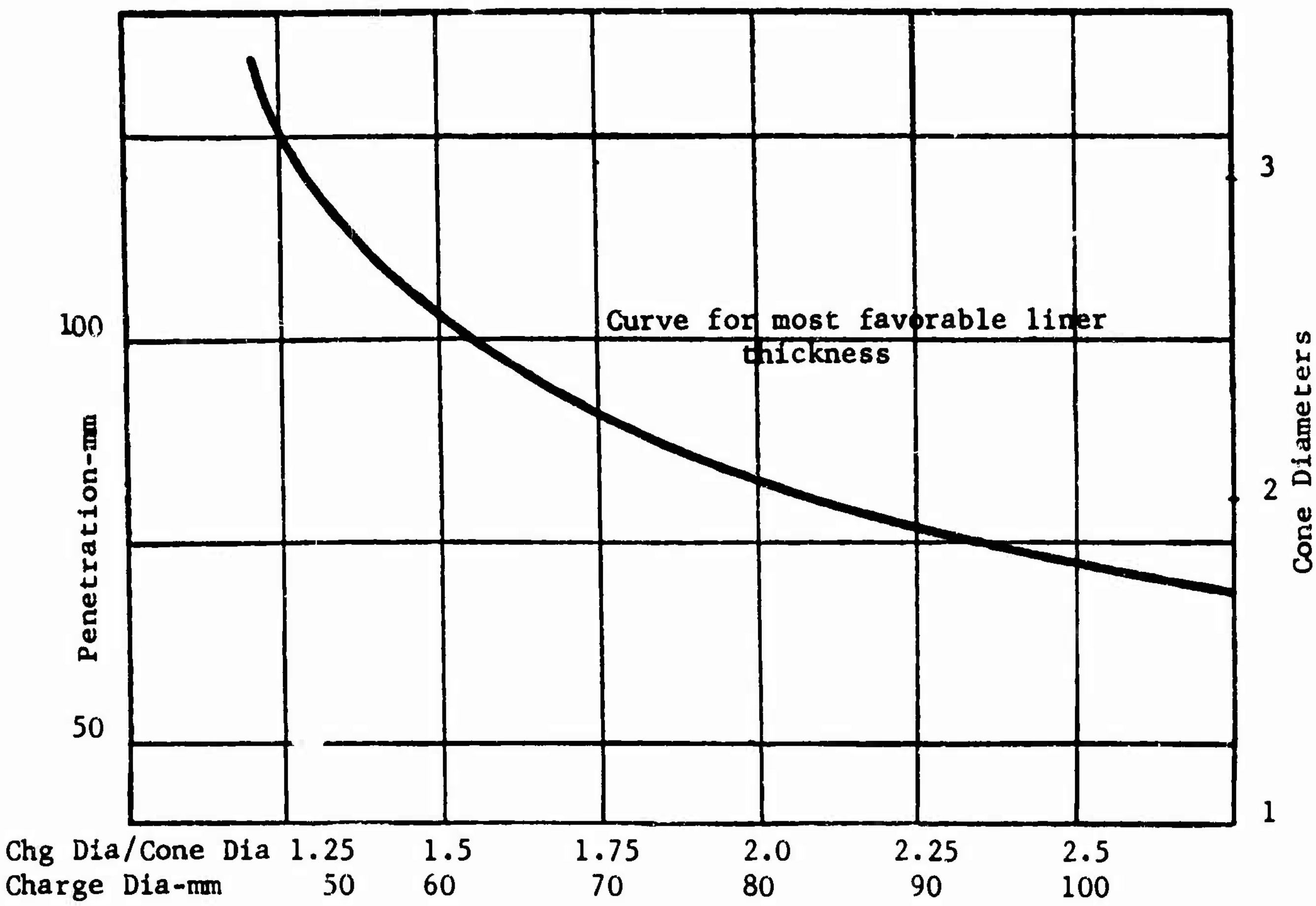


Figure 7. Effect of Charge to Cone Diameter Ratio on Charge Penetration . (From Figure 9 of Reference 16)

It should be noted from Figure 7, that a decrease in penetration effect takes place at constant cone diameter, with increasing charge diameter, despite the larger amount of explosive used. This is explained by the fact that, at the larger charge diameters, the difference in particle velocities of the jet and the jet length decrease.

For reasonable charge designs, if the cone diameter is increased and the other dimensions of the charge and the standoff

changed proportionally, a corresponding increase in target penetration will take place. Because such relationships exist, the various dimensions and the jet effect are usually described in terms of the equivalent number of cone diameters.

Other factors, which influence the cavity effect, are the booster size and external charge shape. The booster must be designed and placed such that the necessary detonation is produced.

The shaping of the charge in the booster region is important, as well as accurate axial symmetry. For example -- a charge type (a) below is capable of producing a jet of greater penetrating power per unit weight of explosive than a cylindrical charge (b) with a length greater than the maximum effective length, L.

STANDOFF DISTANCE

The standoff distance at the time of functioning, to a large extent determines the effectiveness of the shaped charge. The minimum distance is governed by the space required for formation of the proper jet length before target attack. An excessive standoff distance, conversely, permits breakup of the jet before target penetration and consequently poorer performance. In the following Figure 8, it can be seen that target penetration will increase to a maximum generally between 0 and four cone diameters depending upon the apex angle.

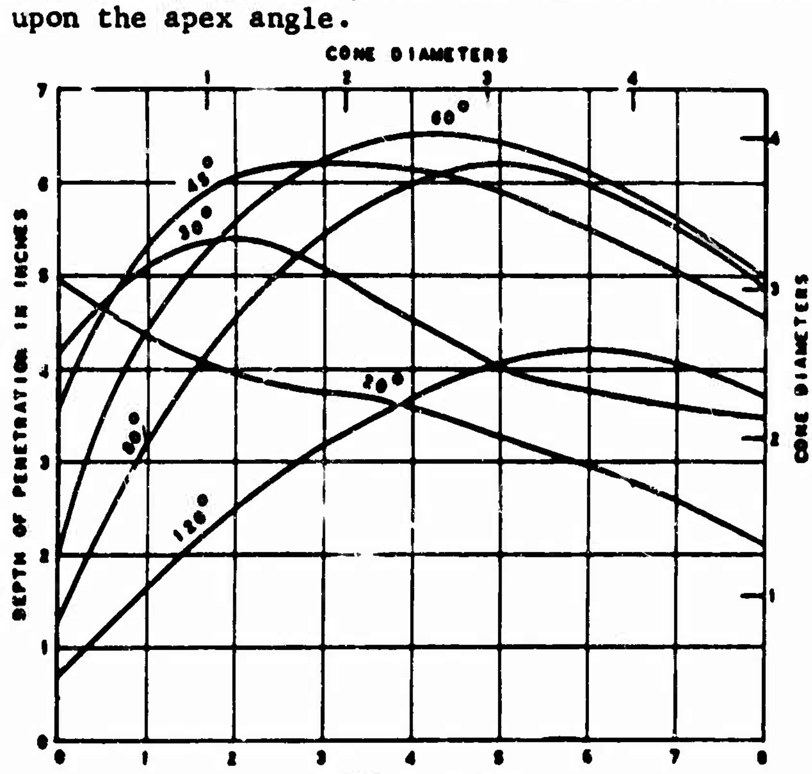


Figure 8. Standoff vs. Penetration (Reproduced from Figure 6, Reference 3, for steel conical liners of 1-5/8" diameter and various apex angles.)

Liner material characteristics will also alter standoff requirements for constant cone dimensions as described in Figure 9.

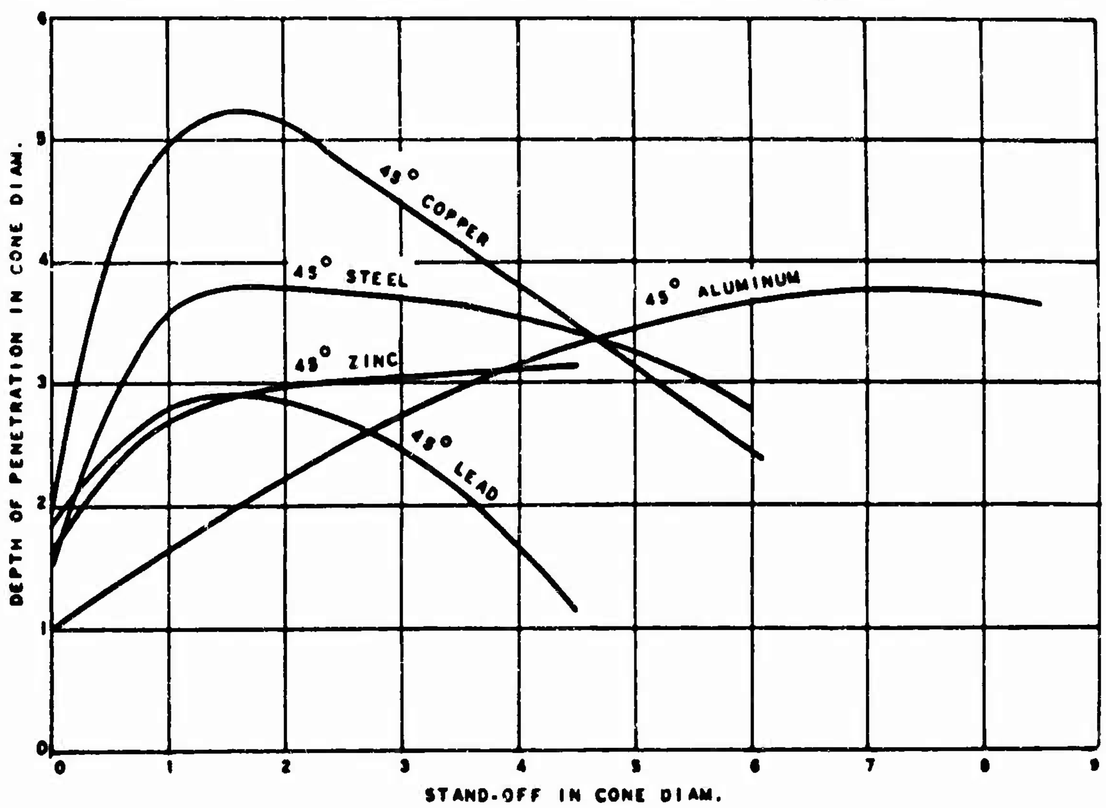


Figure 9. Standoff vs. Penetration by Material (Reproduced from Figure 8, Reference 3.)

It is obvious from this data that aluminum's physical characteristics permit development of a longer jet, which requires standoffs which are abnormally large for many military applications. Most liner materials will provide maximum penetration at one to three cone diameters for 45° angle cones.

For underwater applications of shaped charges the standoff must be provided as an air space.

Figure 10 describes the relationship between the range in water and the air space for various angle cones of different materials that provide penetration of ¼" mild steel targets.

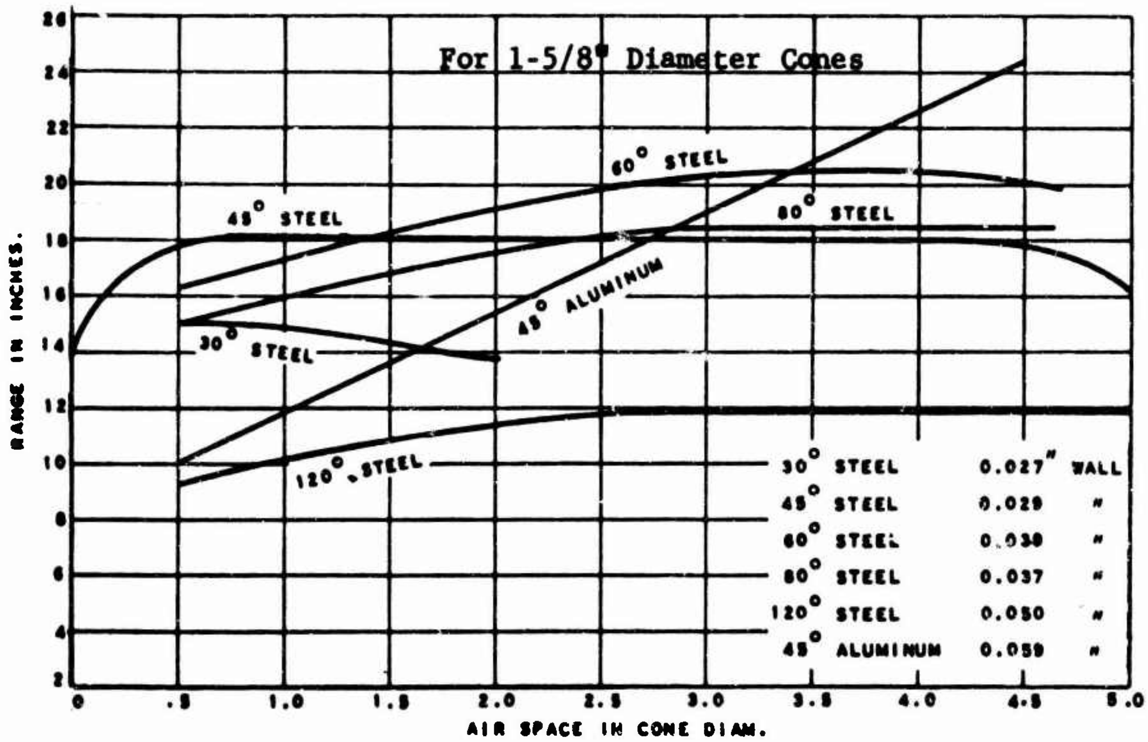


Figure 10. Air Space vs. Range (Reproduced from Figure 9, Reference 3)

CONE ANGLE

The effect of cone angle on liner thickness requirements has been discussed. Figure 11 describes the results contained in translated German documents. Penetration falls off with increasing cone angle using constant charge diameter, cone diameter and standoff.

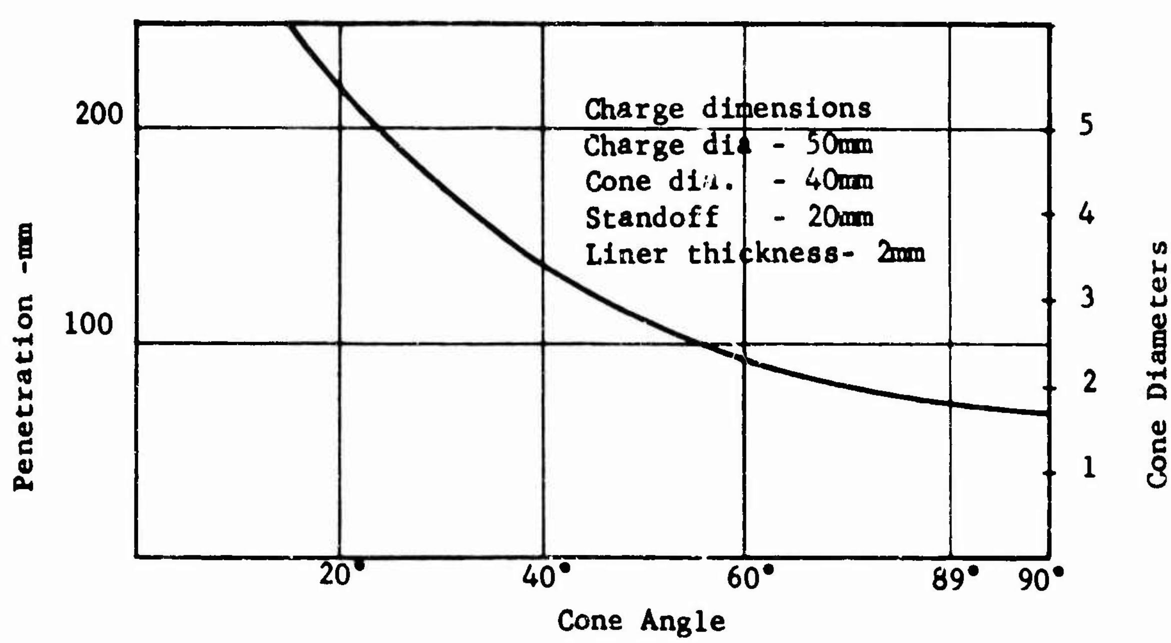


Figure 11. Effect of Cone Angle on Penetration (From Figure 14 of Reference 16)

In this presentation, optimum standoff was not used for the various cone angles tested. A family of curves, each describing penetration at a particular standoff, would be required to describe the effect of cone angle completely.

Available data from NAVORD Report 1248 (Reference 3) indicates similar curves at various standoff values. It should be noted that the curve is altered somewhat when the optimum standoff for each cone angle is used.

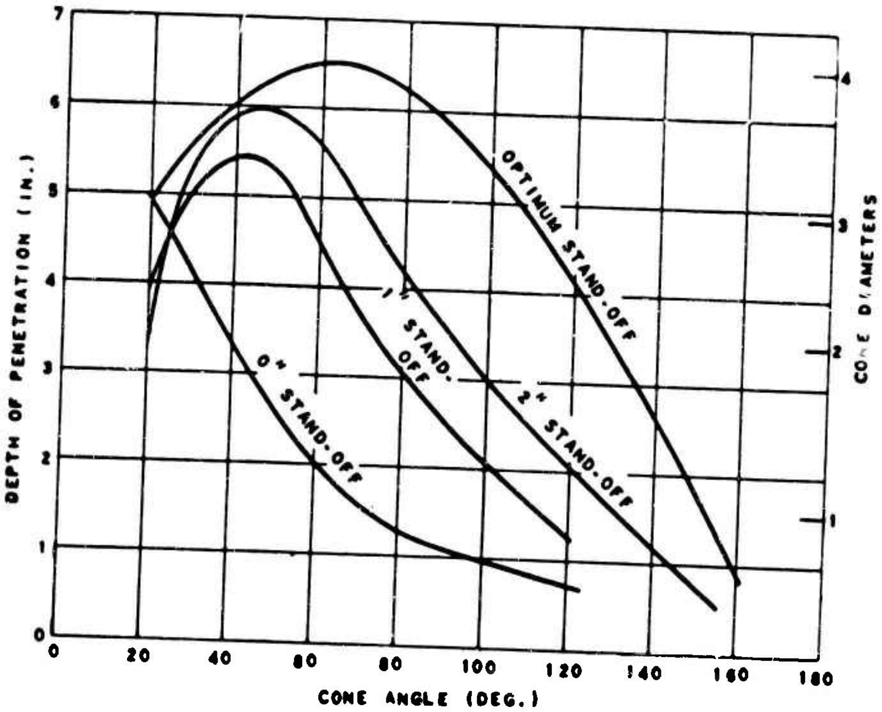


Figure 12. Cone Angle vs. Penetration by Standoff. (Reproduced from Figure 7, Reference 3.)

ALIGNMENT AND CHARGE INACCURACIES

Serious impairment of jet formation and subsequent penetration will result from any of the following:

Imperfections such as air bubbles near the base of the liner.

Misalignment of more than 0.5° between the cone and charge axes.

Cone elipticity of only 1.7% (10% drop in penetration).

Foreign objects inadvertently located in explosive cavity.

The following data were obtained by deliberate misalignment of cone and charge axes or displacement of cone and charge axes:

TABLE 3 (Reference 9)

EFFECT OF AXES ALIGNMENT
OF
1-5/8"-44° CONES ON PENETRATION

Angle Between Cone and Charge Axes	Penetration Depth Normal to Surface-Inches	
	6" Standoff	2" Standoff
0°	5.1	4.9
0.5°	3.5 5.3	---
1.0°	2.3 3.1 2.2 2.3	---
2.0°	4.0 3.3 3.3	4.5 3.3
4.0°	2.0 3.2 2.3	---

TABLE 4 (Reference 9)

EFFECT OF LATERAL CONE DISPLACEMENT
ON
PENETRATION

Lateral Displacement of Cone Axis relative to Charge Axis	Penetration Depth Normal to Target Surface-inches	
	6" Standoff	2" Standoff
0	4.5 4.2	3.7 3.9
1/64	3.4	---
2/64	3.0 2.9	3.7 2.9
5/64	1.9 2.3	---
7/64	1.5	---
9/64	2.1 2.1	---

CHARGE ROTATION

The rotation imparted to shaped charges to insure projectile flight stability reduces the depth of jet penetration. The jet is subjected to the same centrifugal forces as the projectile, which results in reducing the density of the normally extremely small diameter jet. The diameter extension at two rotational speeds is shown in Figure 13. Thus the penetration efficiency may drop as much as 50% as seen from Figure 14.

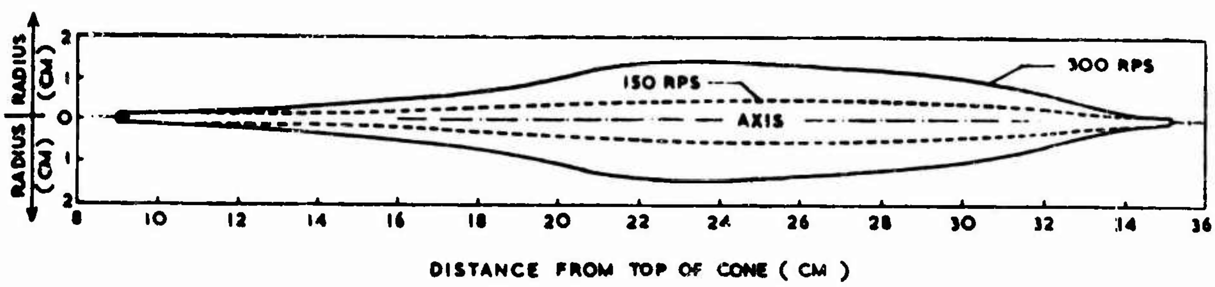


Figure 13. Calculated profiles of the Jet at 50μsec after the Detonation wave had passed the base of the liner and the equipment was rotating at 150 and 300 rps (From Figure 2 of Reference 19)

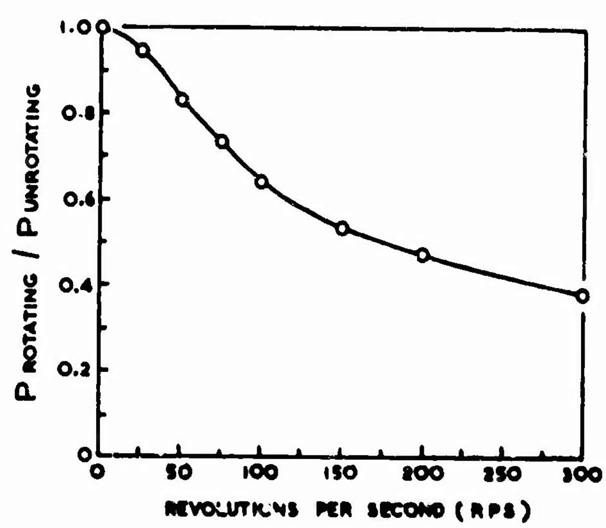


Figure 14. Ratio of the depth of Penetration by Rotating Charge/depth of Penetration by unrotating Charges at 7.62 cm standoff distance in mild steel targets as a Function of the Speed of Rotation of the Standard M9A1 Steel Liner in the Standard C.I.T. laboratory charge (From Figure 1 of Reference 19)

This sensitivity to rotation points up the need for a method of spin compensation or use of non-rotating fin-stabilized projectiles, such as the anti-tank rockets.

IMPACT ANGLE

The impact angle, θ, between the shaped charge axis and the target surface will also alter the penetration normal to the target surface. This can be described by the following relationship:

$$D = P \sin \theta$$

Where D = effective penetration

P = depth of penetration of jet

θ = angle between target and charge axis

Beyond a certain impact angle the depth of penetration is markedly reduced and non-uniform from round to round. This variability is due primarily to fuze action.

The following generalizations can be made concerning impact angle:

The critical angle varies for different type of projectiles.

The critical angle is greater for rotating than for non-rotating projectiles.

The critical angle is greater for heavy projectiles than for light projectiles.

CHARGE CONFINEMENT

The effect of charge confinement on liner wall thickness has been described in Figure 2. In addition it can be said that increased confinement does increase the hole diameter and hole volume; however, the corresponding problem of shrapnel must be considered also.

In many instances the degree of charge confinement depends upon projectile requirements with some sacrifice of shaped charge performance. Excessive confinement is necessary in artillery projectiles because of the severe setback and rotational forces encountered during firing. On the contrary, minimal confinement is generally used in rocket warheads, where excess weight must be eliminated and launching requirements do not demand rugged construction.

GENERAL SCALING RELATIONS

As mentioned previously a linear relation exists for scaling charges of the same cone shape. Using this concept, penetration can be increased by increasing cone diameter, provided that the apex angle is held constant and the charge diameter, length and confinement; liner thickness, standoff; and booster dimensions are each increased linearly.

Such a homologous family of shaped charges, as indicated in the following Table 5 will produce scaled penetration depths at scaled standoff distances.

TABLE 5 (From Reference 6)

RELATIONSHIP OF CHARGE AND CONE DIMENSIONS
FOR
42° COPPER CONES PROVIDING 6 CONE DIAMETERS
OF
PENETRATION INTO MILD STEEL

	Scale Size			
Dimensions	2	3	4	Δ Change
Standoff of 3 cone dia (in)	5.67	8.505	11.34	2.835
Penetration ≈ 6 cone dia(in)	11.34	17.010	22.68	5.670
Cone diameter - inches	1.89	2.835	3.78	0.945
Cone wall thickness inches	0.070	0.105	0.140	0.035
Theoretical Altitude	2.4618	3.6927	4.9236	1.2309
Measured cone mass (gms)	82.53	278.8	662.9	------
Charge length-inches	3.271	4.894	6.525	1.627
Charge diameter-inches	1.892	2.837	3.782	0.946
Charge casing wall thickness(in)	0.237	0.354	0.472	0.117
Booster: Tetryl pellet dia-in.	0.683	1.042	1.378	-----
Tetryl pellet length-in.	0.455	0.683	0.912	0.223

A number of aids for scaling shaped charges have been evolved based upon the relationships already discussed. These are presented for specific target materials and usually for particular types of cone metal.

The German documents established a form for scaling up a 40° angle conical shaped charge. By choosing a desired penetration, the standoff, charge diameter, cone diameter and liner thickness are specified.

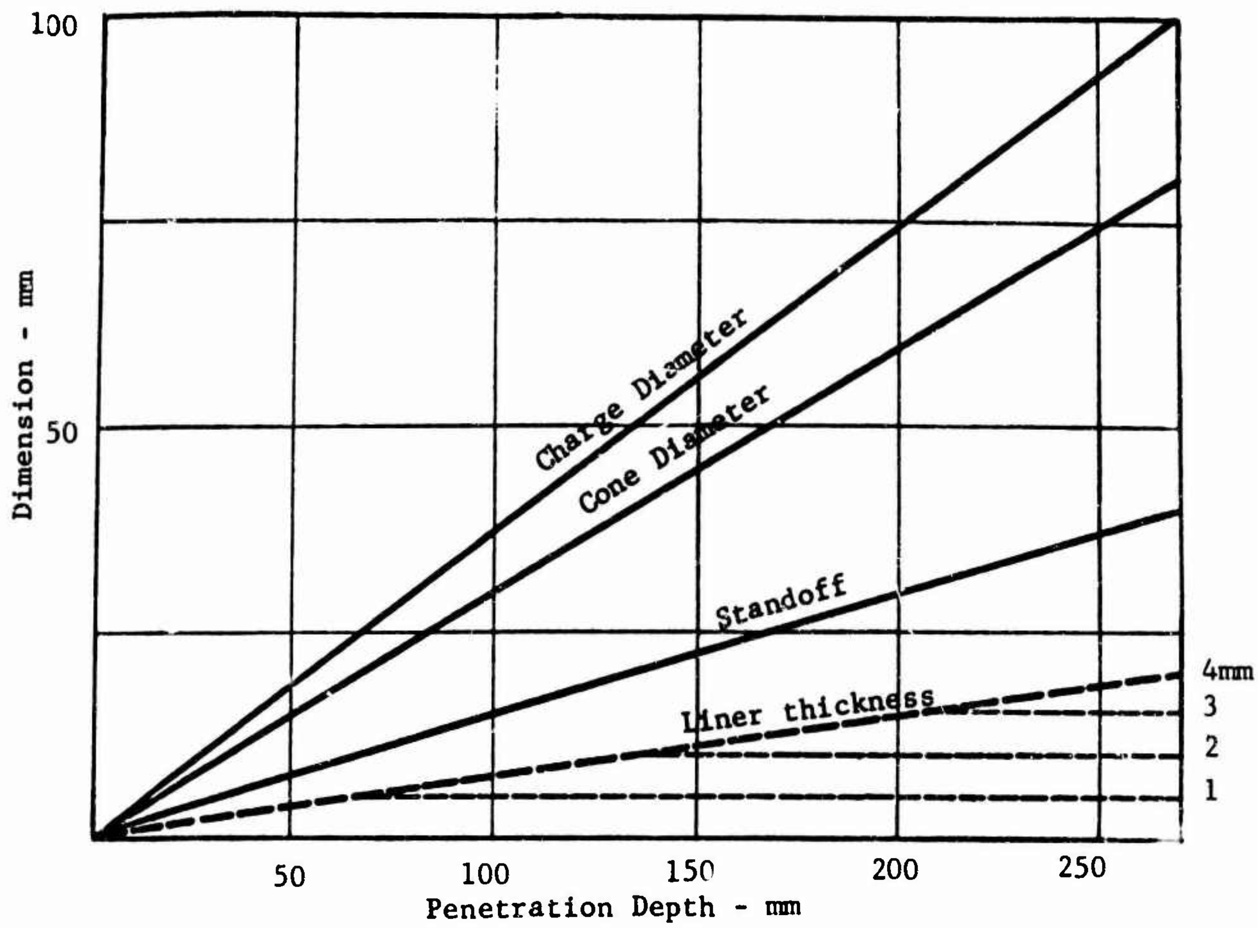


Figure 15. Design Graph for Scaling of 40° Conical Shaped Charges (From Figure 6 of Reference 16)

For example, if it is desired to penetrate 200mm with a 40° conical charge, the following cone dimensions should be used:

Charge diameter - 75mm

Cone diameter - 60mm

Liner Thickness - 3mm

Standoff - 30mm

Another German scaling law for 30° cones was drawn up using the cone diameter for some relationships.

Model Law for a 30° Cone with Iron Liner

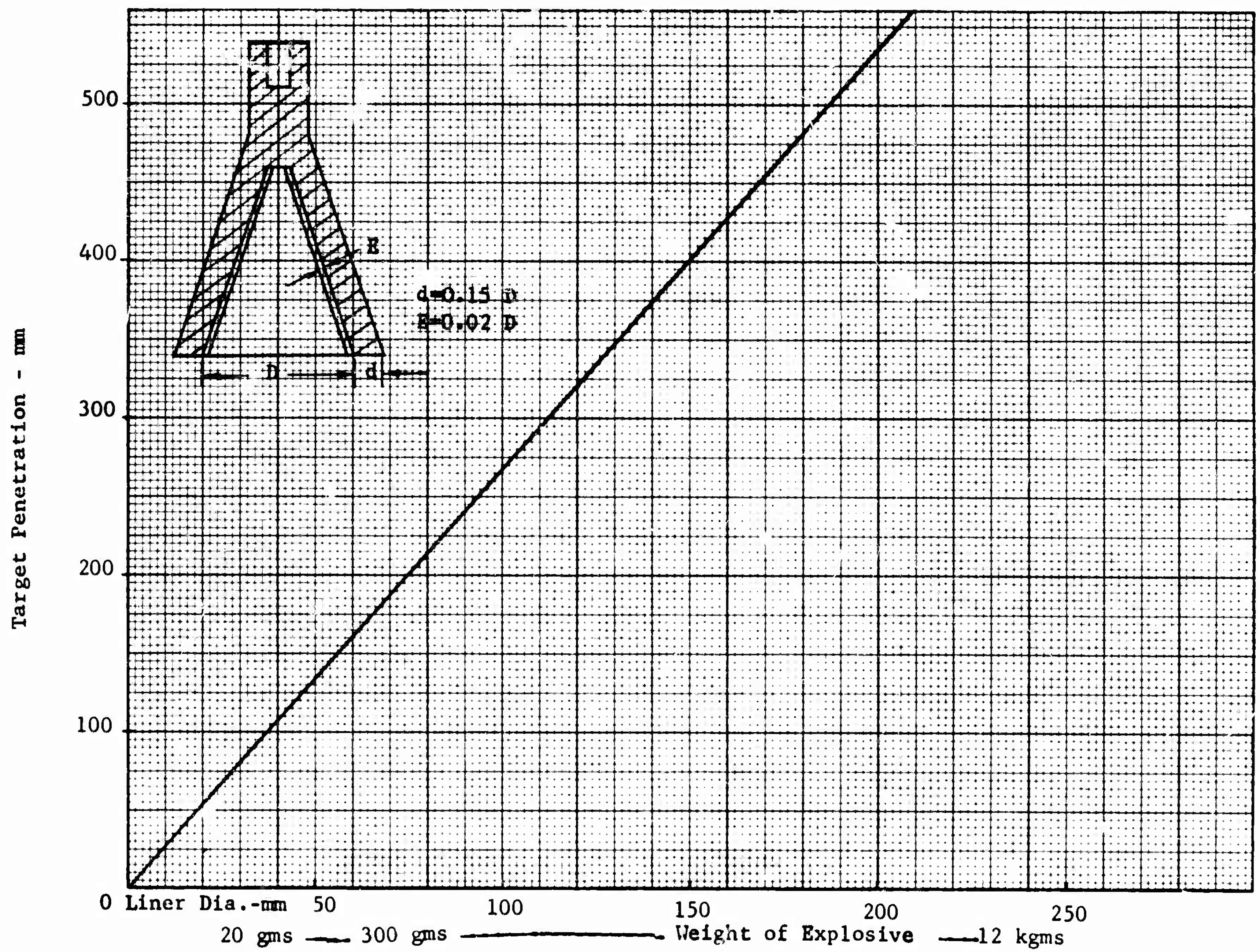
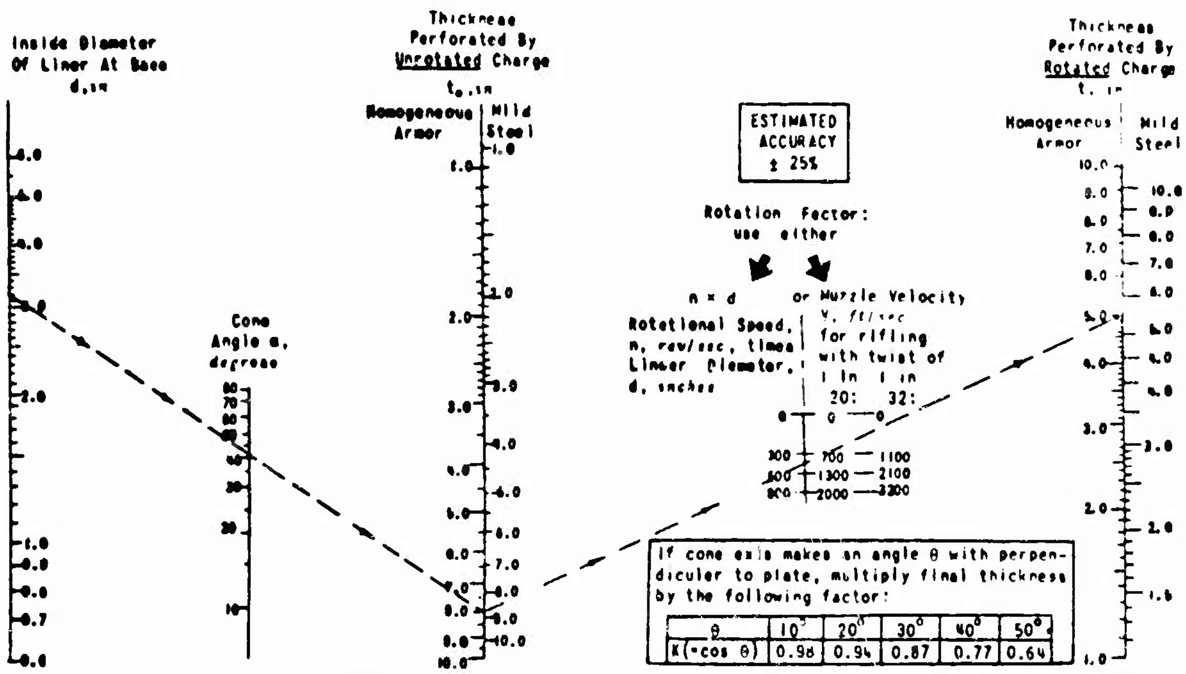


Figure 16. (From Figure 21 of Reference 15)

A design nomograph for perforation of homogeneous armor has been developed from performance records of actual weapons. Included in this presentation are provisions for adjustment of penetration effects due to rotation and charge to target inclination.



θ	10°	20°	30°	40°	50°
K(=cos θ)	0.98	0.94	0.87	0.77	0.64

EXAMPLE: At normal incidence, an HEAT 105mm M67 having a muzzle velocity of 950 ft/sec and a twist of 1 in 20 will perforate about 5 in of armor, as shown by the index lines. At 30°, the performance will be about 5 x 0.87 = 4.3 in.

The nomogram gives thickness of homogeneous armor perforated by Munroe jets from cone-end hollow charge projected weapons. The underlying empirical equation, deduced from performance records on actual weapons is

$$t = \frac{0.89\ d\ \cos\theta}{\sin(\alpha/2)}\ f(nd)$$

where $f(nd)$ = 1.0, 0.69, 0.57, 0.48, for nd = 0, 300, 600, 900 r.p.s. × in respectively. (see notation on nomogram.)

Factors such as thickness and material of liner, type and density of explosive, confinement of charge, stand-off distance, etc. are not included in the relation, although changes in these quantities are responsible for some variation in observed results. With the empirical relation used, scatter in the data precludes making a distinction between *depth of penetration* in massive plate and *thickness* of plate *perforated*. Thus the present relation will be useful in estimating performance of any weapon designed according to reasonable practice, but should be considered a rough guide to be used only in the absence of experimental data.

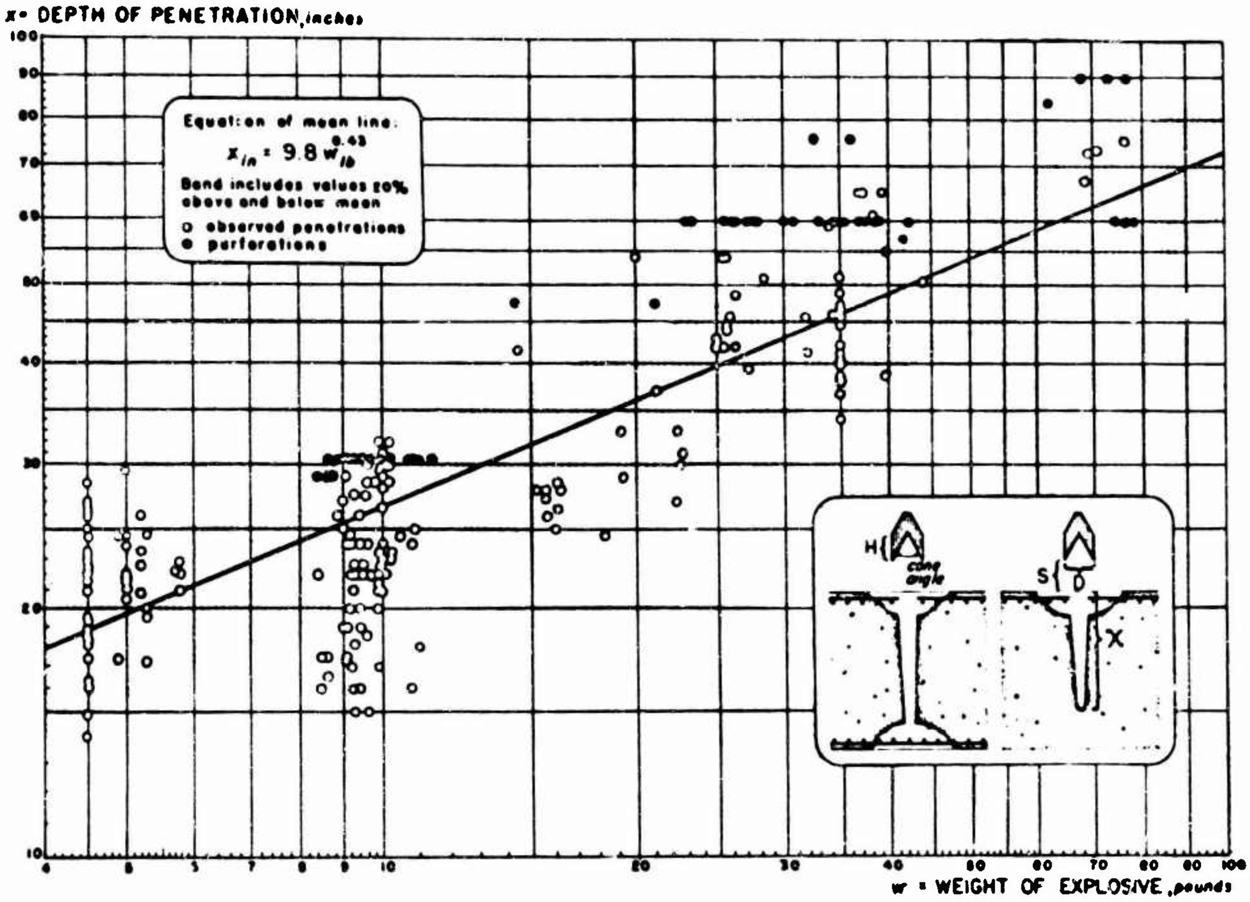
Basic data are mainly for projectiles having steel liners and filled Cyclotol or Pentolite. Explosives combining high power with high rate of detonation give greatest target damage. As the equation above shows, rotated projectiles generally form shallower craters; however, these are likely to be wider than the craters due to static detonation.

PERFORMANCE OF PARTICULAR WEAPONS:

Weapon	Thickness of Armor Perforated, in (normal incidence)
US - HEAT M6A3(Bazooka)	5.3
Grenade M9A1	4.0
HEAT 57mm T-20 E-2	3
HEAT 75mm M66	3.5
HEAT 105mm M67	4.8
Br - PIAT	3.8
HEAT 3.7-in & 95mm	5.0
Ger- Panzerfaust (30, 60 & 100)	8.0
Panzerschreck (Ger. Bazooka)	6.5
Jap- A.T. Conical Hand Grenade	2.8
A.P. Rifle Grenade	2

Figure 17. Penetration of Homogeneous Armor by Weapons with Cone-End Charges (Reproduced from Figure 15 of Reference 3)

For information and comparison with the data given for steel, some additional graphs follow, which present the penetrations into concrete and permafrost.



The graph shows depth of penetration produced in concrete by a cone-end charge placed with axis perpendicular to the slab face. The mean line was determined by a least squares reduction; shaded band includes values 20% above and below mean.

Because of scabbing on rear face (see inset sketches) perforation often results even when slab thickness is greater than the penetration depth that would result in massive concrete.

TYPE OF EXPLOSIVE: Effects are not greatly dependent on explosive type provided charge is thoroughly compact and adequately primed.

BEST - TNT/RDX	Plastic H.E.	GOOD - Pentolite	Nobel 808	POOR - 60/40 Amatol
TNT/PETN	Cyclotol	TNT	Picric Acid	P. A. G.
TNT/CE	P.E.	Lyddite	Tetrytol	

CONE LINING: Dependence on material and thickness is not great.

Materials: BEST - Pressed steel. Forms large slug which may stick in hole, especially if cone angle is less than about 70°; may thus impair insertion of demolition charge.

GOOD - Glass. Hole somewhat shallower but of larger volume than with steel. Less debris is left in hole. Cast brass and cast manganese bronze also good.

Thickness: Various thicknesses used. Experiments indicate optimum value of about 0.1 inch (steel) for a charge of 6-inch diameter, and weighing approximately 10 lbs.

CONE ANGLE: Not extremely critical, but 60° to 80° usually adopted.

LENGTH-DIAMETER RATIO: Values of H/D (see sketches) between ½ and 1 are recommended.

STAND-OFF DISTANCE: The optimum stand-off, S, appears to be between about ½ and 1½ diameters.

CONCRETE STRENGTH: In general, slightly larger but not deeper holes result in softer concrete.

PILLBOX TESTS: Trials indicate that a 75-lb. charge will defeat a 5-ft. thick pillbox wall and throw scab capable of lethal or incapacitating effects on any occupants.

DATA FROM EXPERIMENTS BY U.S. ENGINEER BOARD AND BY BRITISH MINISTRY OF SUPPLY

Figure 18. Penetration of Concrete by Detonation of Cone-End Charges (Reproduced from Page 20 of Reference 3)

TABLE 6

CHARACTERISTICS OF ALL CHARGES TESTED (Taken from Page 4 of Reference 1)

Type	Total Wt. (lb)	Expl.Wt. (lb)	Type Explosive	Cone Material	Cone Angle (deg)	Cone Thickness (in.)	Cone Outer Diam. (in.)	Cone Wt. (lb)	Container
M3	40.0	30	Composition B or pentolite	Steel	60	0.150	9.5	5.6	Sheet Metal
20 lb.Exp.	28.8	16.8	Composition B	Copper	45	0.190	6.0	4.9	Fiber
M2A3	15.0	11.5	Composition B or pentolite	Glass	60	0.350	6.0	1.7	Fiber
M2	13.0	10.0	Pentolite	Glass	60	0.350	6 [illegible]	1.7	Cloth and Cardboard
5 lb Exp.	5.2	2.4	Composition B	Copper	42.5	0.110	3.5	0.8	Fiber
Jet Tapper	0.28	0.14	RDX	Copper	80.0	0.033	1.75	0.03	Plastic

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Picatinny Arsenal, Dover, New Jersey

SHAPED CHARGE SCALING

Oscar A. Klamer

Technical Memorandum 1383, March 1964, 29 pp, figures, tables. Unclassified report from the Artillery Ammunition Laboratory, Ammunition Engineering Directorate.

The design of shaped charge items is governed by two primary considerations – the required target penetration and the allowable configuration permitted by the delivery technique to be used. The penetration characteristics have been studied extensively to establish the effects of explosive, explosive configuration, size, liner material and shape, orientation relative to the target, spin and symmetry.

(over)

UNCLASSIFIED

1. Shaped Charges

I. Klamer, Oscar A.

UNITERMS

Shaped charge scaling
Explosive configuration
Spin
Symmetry
Mild steel
Target penetration
Composition B
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Ednatol
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Cone parameters
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Hemispherical liners
Ductile metal liners
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